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PLANETOLOGICAL INVESTIGATIONS

or

Investigations of Selected
Martian Regions Using Primarily
Mariner 9 Data

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PLANETOLOGICAL INVESTIGATIONS

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Final Report

Dr. Chapman of Planetary Science Institute was funded to engage in two tasks during 1976. The first concerned comparative planetological analyses of cratering and geomorphological processes. The second concerned asteroid fragmentation processes. Through a mistake in wording of the contract, the title of the previous year's project ("Investigations of Selected Martian Regions Using Primarily Mariner 9 Data") was used although the research tasks were somewhat different. In late 1976, a no-cost extension was granted through spring 1977.

The major goals of both research projects were achieved. They have been reported on in greater detail in separate publications and abstracts. They are appended here so as to constitute the Final Report.

Appendix 1: "Formation and Obliteration of Large Craters on the Terrestrial Planets" by Clark R. Chapman. In "Reports of Planetary Geology Program, 1976-1977" (R. Arvidson and R. Wahmann, compilers), NASA TM X-3511, 103-104.

Appendix 2: "Cratering and Obliteration History of Mars" by Clark R. Chapman and K. L. Jones. Ann. Rev. Earth Planet. Sci. 1977, 5, 515-540.

Appendix 3: "The Collisional Evolution of Asteroid Compositional Classes" by D. R. Davis and C. R. Chapman, <u>Lunar Science VIII</u>, 224-226.

Appendix 4: "Asteroid Fragmentation Processes and Collisional Evolution" by Clark R. Chapman, Donald R. Davis, and Richard Greenberg. <u>In</u> "Reports of Planetary Geology Program, 1976-1977" (R. Arvidson and R. Wahmann, compilers), <u>NASA TM X-3511</u>, 72-73.

Appendix 5: "Report on Paper presented at PGPPI Meeting in St. Louis, May 1977"

Appendix 6: "Comparison of Chapman/Davis Collisional Model with Bias-Corrected Asteroid Data."

APPENDIX 1

"Formation and Obliteration of Large Craters on the Terrestrial Planets"

by

Clark R. Chapman

Formation and Obliteration of Large Craters on the Terrestrial Planets.
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The craters on the moon, Mercury, and Mars and other terrestrial planets testify to a long history of bombardment by interplanetary objects. The degradation and obliteration of these craters on the cratered terrains of these planets, and the even more complete removal of large craters from the Earth, Venus, and the plains units of the other three bodies, testifies to the large-scale geomorphological processes that have acted during part or all of the history of the terrestrial planets. Studies of these craters, and their stratigraphic relationship to other geological features, can help to address questions in two fundamental areas of solar system science: (i) the distribution and evolution of small-body populations in the inner solar system and (ii) the geomorphological evolution of the surfaces of the terrestrial planets.

This general subject has been in a state of considerable flux during the past couple years as Mariner 9 interpretations of Martian cratering became crystallized and as preliminary hypotheses about comparative planetological cratering were developed based on Mariner 10 imagery of Mercury. Several common assumptions about cratering have been under attack, in particular the once-prevalent belief that the heavily cratered units on the moon (and perhaps Mercury and Mars as well) represent a condition of saturation equilibrium (1,2,3,4). Several important new hypotheses for terrestrial planet cratering have been offered, as well, including the suggestion that the crater populations on the cratered terrains of Mercury, the moon, and Mars are all predominantly due to an intense period (perhaps episode) of bombardment by the same population of interplanetary bodies at some early time in solar system history (roughly 4 b.y. ago).

A recent tendency by many investigators has been to adopt, or even deduce, absolute chronologies for the geologic evolution of the surfaces of the terrestrial planets which places not only the formation of large craters, but also large-crater degradation and formation of plains units, in the distant past (prior to 3 b.y. ago). I have argued elsewhere (5) that absolute chronologies are available only for the moon and the Earth, and that ages are poorly constrained for Mercury and Mars. The recently proposed "possible new time scale" for Mars by Neukum and Wise (4) is, like its predecessors, based on certain controversial assumptions. Neukum and Wise treat Martian and lunar highland crater populations as production functions dating from 4.4 b.y. ago. Their chronology is further based on an assumed age for the present surface of Phobos.

The notion that the lunar highland crater population is unsaturated is at least an arguable proposition (6). Despite the lower spatial density of Martian craters, however, their shallow depths (7,8,9) and spectrum of degraded morphologies rule out their being a production function. Rather the large Martian craters constitute a population that is, or has been, in equilibrium with rather extensive endogenic obliteration processes.

Chapman and Jones (6) have now reconciled their earlier models for Martian cratering and obliteration (10,11). Readers are directed to this review article for what I trust is a clearer exposition of the models than has been previously available. From the morphologies of the largest Martian craters, it appears that they were obliterated by a large-scale, efficient obliteration process -- probably of endogenic orgin, but possibly due to the cratering process itself -- acting contemporaneously with the cratering. Similar conclusions were reached previously by Chapman, Pollack, and Sagan (12) and by Soderblom et al. (13). The morphologies of the middle-sized craters on Mars provide dramatic evidence for a subsequent episode of obliteration in intermediate Martian history. By "episode" I mean that the ratio of obliteration rate to cratering rate increased and then decreased again. Since this period of obliteration appears, from stratigraphic relationships, to be roughly coincident with the formation of the ubiquitous furrows in the cratered terrains and with the first formation of northern plains (the so-called "cratered plains" units), it is plausible to link this important event in Martian history with both the beginning of major Martian volcanism and with a period of more clement atmospheric conditions on the planet. This further suggests that Martian atmospheric evolution may have been causally connected with volcanic evolution. The distribution of small craters on Mars implies that post-obliterative-episode epochs on Mars have seen surprisingly little net erosion and obliteration.

We cannot state when, in absolute chronology, this obliterative event occurred. But acceptable chronologies (5) place it anywhere from about ½ b.y. ago to the later stages of the intense early bombardment on Mars which probably occurred, as on the moon, about 4 b.y. ago. If this important epoch of Martian geologic evolution occurred in relatively recent history, it would imply that Mars was geologically quiescent following the early heavy bombardment and that it only rather recently became geologically active. If the other extreme chronology is accepted, it would imply that virtually all of the geologically, geophysically, and meteorologically interesting evolution of the planet occurred during and shortly after the period of intense early bombardment (only volcanism in the immediate vicinity of the Tharsis Montes would then have occurred more recently). Intermediate chronologies include those that have major Martian plains units forming throughout the planet's history.

We should be careful about incorporating our preconceptions from terrestrial and lunar experience into our hypotheses for Mars. The relevant geomorphological and geological processes manifest on the surface of Mars are driven, ultimately, by the thermal evolution of the interior of Mars. Plausible scenarios for the thermal evolution of Mars do not yet permit us to choose one chronology over another.

Further understanding of the absolute chronologies for Mercury and Mars must await either (i) substantial improvement in the cataloging of small asteroids and understanding of their orbital evolution or (ii) the return of datable samples from those two planets. Since conclusive results from either approach are not imminent, the best we can do in the meantime is to formulate plausible hypotheses for planetary geological evolution.

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APPENDIX 2

"Cratering and Obliteration History of Mars"

by

Clark R. Chapman and K. L. Jones

Ann. Rev. Earth Planet. Sci. 1977. 5:515–40

CRATERING AND OBLITERATION HISTORY OF MARS

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INTRODUCTION

The craters on Mars testify to a long history of bombardment by interplanetary objects. Further, the numbers of craters and their morphologies record the effects of erosion and deposition that have been altering the face of Mars throughout the history recorded by observable craters. If this record of cratering and obliteration can be related, through the stratigraphic principles of superposition, to the formation of such structures as volcanoes, stream channels, and lava flows, then we will know the broad outlines of the evolution of the Martian surface. Finally, if we can relate the cratering history of Mars to the histories of the Earth, the Moon, Mercury, and other bodies, then we can compare the evolution of terrestrial planets as a group.

Since the first orbital pictures were returned from Viking I, there has been renewed interest in the complex processes of volcanism, aeolian abrasion and deposition, collapse and sapping of underground frozen volatiles, fluvial processes, and epochs of more clement and rainy weather that have shaped Martian geomorphology in regionally heterogeneous ways. The great increase in resolution of Viking orbital pictures, which far surpasses the resolution of Mariner 9 pictures, and the close-up views from the Viking landers are greatly augmenting our knowledge of Mars (cf Carr et al 1976). Our review is based mainly on the pre-Viking literature. Yet we have been cognizant of preliminary interpretations publicly reported during the first months following the arrival of the first Viking at Mars, and the emphases in this review have been influenced thereby. In particular, because of the great geological complexity of Mars revealed by Viking beyond that appreciated from Mariner 9, we approach our task of a global synthesis of Martian cratering with some trepidation.

Craters have attributes that make them uniquely useful for deciphering the geomorphological history of a planet. With some exceptions, impact craters have the following traits: (*a*) They form a very large sample of similar topographic features that are amenable to statistical analysis. (*b*) They have formed throughout planetary history, although there are very few data constraining the time dependence of the rate of crater formation for Mars. There might be a degree of correlation among the cratering rates on the different terrestrial bodies. (*c*) Impact craters mainly occur at random locations on a planet, despite slight global asymmetries. Formation of doublet or even clustered primary craters has occurred and may be common on Mars (Oberbeck & Aoyagi 1972), but such clustering probably can be taken into account. Formation of secondary craters is also important, especially at small diameters, but they often can be recognized and distinguished from primaries by their morphologies and spatial relationships to primaries. Some endogenic craters (e.g. calderas and cinder cones) are even more easily recognizable. (*d*) The original shapes and traits of newly formed craters of the same size (e.g. diameter/depth ratio, wall terraces, ejecta blankets) are roughly similar. Thus measured departures of a crater's appearance from "fresh" morphology probably represent degrees of modification of the crater. Other adjacent topographic features (such as river channels) of similar scale and stratigraphic age may be expected to have undergone a similar degree of modification. (*e*) Degradation of a crater is generally an irreversible morphological process until the crater finally disappears altogether because of the cumulative erosion or deposition (exhumation is an exception discussed later).

To the degree that these generalizations are true, departures from a uniform

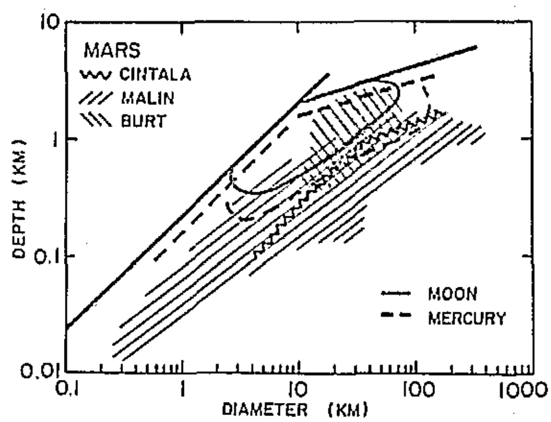

Figure 1 Depth/diameter plots for Martian craters, compared with the Moon and Mercury. Straight lines for the Moon and Mercury are mean fresh crater distributions; regions occupied by degraded craters are encircled below. Mars data, and some of the comparisons, are from Cintala, Head & Mutch (1976), Malin & Dzurisin (1977), and Burt, Veverka & Cook (1976). The Mars data have been acquired with a variety of techniques, most subject to appreciable systematic error. It is uncertain to what degree the apparent difference between the crater depths on Mars and Mercury is established.

distribution of fresh craters around a planet bespeak important processes—whether exogenic or endogenic[1] in origin—which, in the process of modifying the craters, must also have modified other surface topography. For instance, the gross dichotomy of Mars into hemispheres, one rather densely covered by large degraded craters and the other sparsely populated with small fresh craters, reveals that fundamentally different processes have operated on each hemisphere of the planet.

Although Mariner 9 and Viking pictures have revealed a number of cases in which there are exceptions to our generalizations or in which the geological history has been too complex to be accounted for in broad statistical terms, we believe there is a sound basis for attempting to delineate relative and absolute histories of major global regions on Mars. By and large, we believe that the relative chronology is more firmly established than some planetologists believe. On the other hand, at least the more popular accounts seem to us to be too precise in specifying the *absolute* ages of Martian features. The geomorphological evidence for cyclical episodes in Martian geomorphological history, frequently raised in the context of the search for Martian life, is not established; neither is cyclical evolution excluded by present data.

EARLY INTERPRETATIONS

Two cogent observations were made from the Mariner 4 pictures, which were received in 1965. The first is that most Martian craters are highly degraded, indeed much more so than lunar uplands craters. Recently, this obvious fact has been demonstrated quantitatively in terms of crater depth/diameter ratios (Figure 1). The second observation, due to Öpik (1965, 1966) and amplified upon by Hartmann (1966) (see also Binder 1966, and Leighton et al 1967), is that relative to a particular power law fitted to the Martian crater diameter-frequency relation at large diameters, there is a paucity of craters with diameters smaller than ~30 km (estimates varied from 20 to 50 km; Figure 2, left portion). Öpik suggested that older small craters had been entirely obliterated by the same processes responsible for degrading the morphologies of more recent craters less than 30 km in diameter as well as of the older large craters.

It has been assumed that craters were formed by impact of a population of collisionally evolved asteroids, which probably follows a power-law distribution (Dohnanyi 1972) and which, through scaling relationships between asteroid diameter and resultant crater diameter, create a power-law distribution of craters (shown as the right-hand production function, slope = -3, in the left portion of Figure 2). Although there are some observational uncertainties in defining the incremental frequency distribution of asteroids, it probably can be approximated by a power law with an exponent between -3 and -3.5, which results in a similar exponent for the crater distribution that increases to about -4 for the largest craters governed by gravity scaling. Öpik showed that a simple obliterative process, such as dust

[1] By *exogenic* we mean processes related to impact cratering. All others are *endogenic*, including atmospheric, surficial, and subterranean processes.

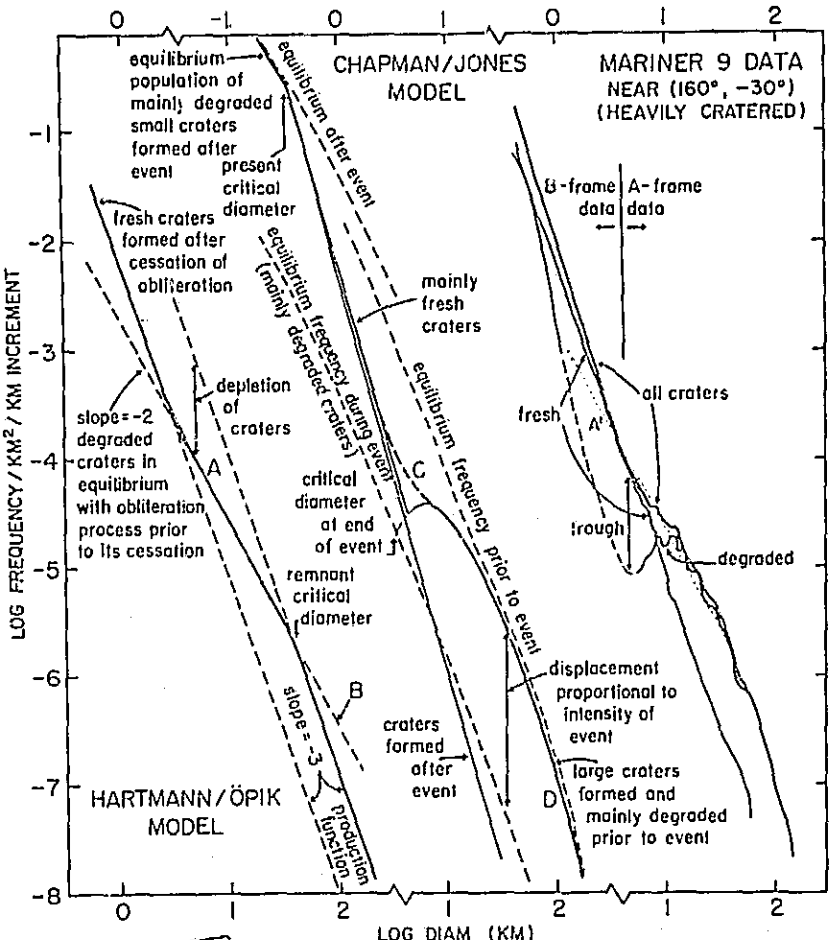

Figure 2 Comparison of two models for Martian cratering and obliteration with data from a heavily cratered unit. Thicker lines represent the present total crater population; other lines represent components. Left panel: Pre-Mariner 9 model due to Öpik (1965), Hartmann (1973), and others. A power-law production function is depleted and reaches equilibrium with an obliteration process at diameters less than a critical diameter; then the obliteration process ends and the subsequent population of mainly small craters retains fresh morphologies. Middle panel: Model due to Jones (1974) and Chapman (1974a), discussed in the text. There was an interval ("event") of greatly augmented obliteration rate that shifted the crater population to a lower equilibrium curve, producing the kink in the total crater curve (near *C*). Right panel: Observed crater frequencies from Jones' (1974) region 32, augmented by some unpublished, small-crater B-frame data due to Chapman (the dashed line indicates inadequate data).

deposition, which continuously degrades and obliterates craters at rates inversely proportional to their depths (for constant depth/diameter ratio), results in an equilibrium frequency distribution of slope one unit shallower than the production function (slope = -2 in Figure 2). Öpik's model seemed to fit available Mariner 4 data.

That Öpik's model was incomplete became obvious from Mariners 6 and 7 (Murray et al 1971), although Chapman (1967) recognized disparities even in the Mariner 4 crater data (see Chapman 1974b). At smaller diameters, the *fresh* craters follow a steeper relation than do the more degraded craters; indeed, most craters with diameters less than a few kilometers are fresh (see Figure 2). Therefore, Murray et al (1971), McGill & Wise (1972), and Hartmann (1973) in his Mariner 9 analysis introduced a variant of Öpik's model. They suggested that the processes of erosion have slowed down or ceased so that recent craters, including very small ones, have not been appreciably degraded.

As time progresses, an obliteration process gradually destroys larger and larger members of the first-formed craters on the surface of a planet. As the total crater population moves upward with time on a size-frequency plot, it abuts the equilibrium frequency (*B* in Figure 2), bending over to follow the equilibrium curve at the "critical diameter." The equilibrium population of craters (*A* in Figure 2) consists of a spectrum of morphologies; only the most recent craters are fresh. Subsequent to the hypothesized cessation of obliteration, the production function has recratered the surface to the degree shown by the lower production function, which is added to the remaining two-sloped curve; these new fresh craters dominate the population only at small diameters. The break in slope observed by Öpik and others marks the remnant critical diameter from the earlier epoch of active obliterative processes.

Since the northern-hemisphere plains revealed by Mariner 9 contain chiefly fresh, small craters with frequencies similar to or less than the small-crater frequencies in the cratered terrains, early interpretations of Mariner 9 pictures suggested that those units formed contemporaneously with, and subsequent to, the cessation of crater degradation in the cratered terrains (Hartmann 1973). The cessation of degradational processes was first thought to have occurred in relatively recent Martian history but, as we discuss when we deal with absolute chronologies later, this may not be true.

CRATERING/OBLITERATION MODELS

In separate papers based on Mariner 9 crater morphology data (Jones 1974, Chapman 1974a), we derived a new scenario for Martian cratering and obliteration history. We argued that most of the degraded morphologies of moderate-sized Martian craters (e.g. 10–30 km) were caused by a relatively brief episode of obliteration such that, relative to the cratering rate, the degradational processes were augmented by a factor of five to a hundred or more. Subsequently the

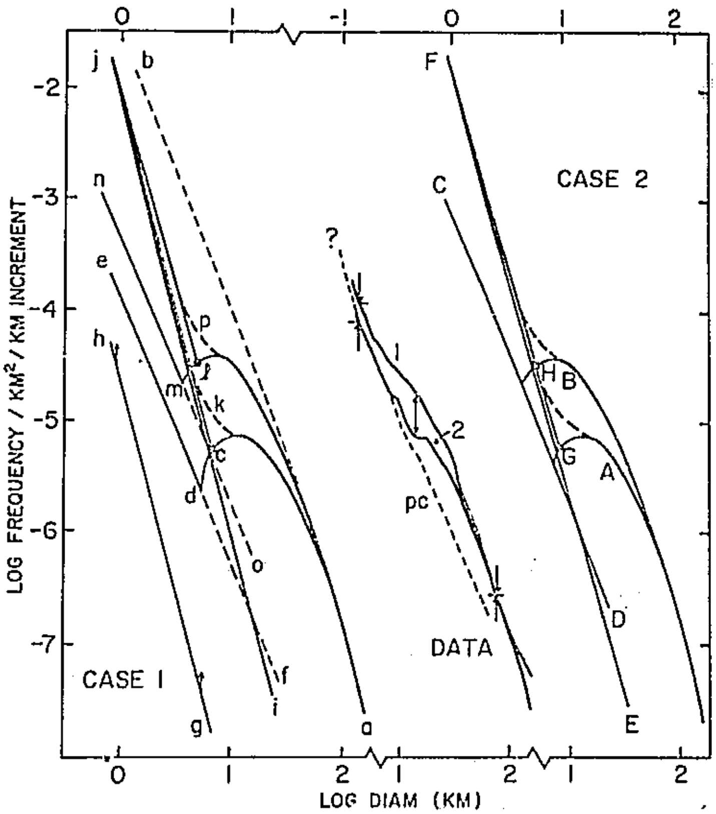

Figure 3 Regional differences in crater frequencies may be interpreted in terms of a crater obliteration event in two different ways. Case 1: Obliteration lasts the same length of time for two regions but is much more intense in one than the other. Before the event, frequencies are in equilibrium along line *ab*. One region undergoes moderate obliteration and a new equilibrium is established along *no*, resulting in frequencies *almn* immediately after the event. The second region undergoes massive obliteration, reaching a lower equilibrium frequency along *ef*, resulting in *acde*. Fresh cratering commences (*gh*) and moves upward to *ij* at present. Observed frequencies for region 1 are the sum of *almn* and *ij* which is *alj* or, for reasons described in the text, *apj*. Observed frequencies for region 2 are, analogously, *acj* or *akj*. Note that *cj* and *lj* are not coincident. Case 2: The obliteration has the same intensity in the two regions but lasts much longer in region 2 than 1. In this case the equilibrium frequency curve during the event is identical for both regions (*CD*), so the addition of the post-event craters (*EF*) results in the same frequency relation for small craters (*GHF*). The region subjected to the shorter event has observable frequencies *BF*, while the other exhibits *AHF*. The middle panel shows total crater data from Mariner 9 A-frame counts for Jones' (1974) regions 1, 24, 29, and 32 (curve 1), regions 19 and 21 (curve 2), and pc units. The data seem more like Case 1 than 2, yet we need better data in the vicinity of the question mark to be sure.

degradation rate declined again to a rate not much greater, and perhaps much less, than the original rate. This final period of low obliteration rate corresponds to the period after cessation of erosion postulated from the Mariner 6, 7, and 9 observations of fresh small-crater populations

The fundamental difference between our interpretation and earlier ones is our explicit separation of the obliteration rate from the cratering rate prior to what all agree has been a low recent obliteration rate. The earlier models of Öpik (1965) and Chapman, Pollack & Sagan (1969) assumed *constant* obliteration and cratering rates. Several investigators (e.g. Hartmann 1971) argued that the Martian cratering rate has changed drastically with time (it was much higher in the past); Soderblom et al (1974) argued further for a strict association between the obliteration rate and the decreasing cratering rate. If there were such a connection, it would suggest that the obliterative process may have been directly or indirectly *caused* by the cratering process. We, on the other hand, interpreted the data as requiring an obliteration rate that, for a while, varied radically with respect to the cratering rate; we have suggested that the episode of obliteration of moderate-sized craters was largely *subsequent* to the early period of cratering, when the rate of cratering is commonly assumed to have been high. Further, we have suggested that the episode might have been related to the period when rainfall occurred on Mars and carved the widespread system of "furrows," or small channels (see section on aqueous processes, below). The apparent simultaneity of the hypothesized obliterative episode with the formation of the first major plains units in the northern hemisphere is possibly suggestive of an endogenic origin for the obliteration process, uncoupled from the early cratering.

In this section and the one that follows we will, with the aid of Figures 2–4, lead the reader through the observations and cratering theory that led us to our conclusions. Later we describe alternative models. Scientists interested in Martian history should understand our formulation, since any theory for Martian cratering and obliteration can be explicable in equivalent terminology to that which we employ here. Despite the apparent complexity of Figures 2 and 3, the logic is fairly elementary. The basic graph is a log-log plot of incremental crater frequency vs diameter. There are simple mathematical relationships between this plot and a commonly used alternative, a plot of log diameter vs log cumulative frequency (they are compared by Jones 1974); the chief difference is that our incremental relations tend to be one unit steeper in slope than cumulative curves.

The cratering rate c on a planet depends on both time, $c_t(T)$ (e.g. a decreasing flux), and diameter, $c_d(D)$ (e.g. $\propto D^{-3}$). The diameter dependence $c_d(D)$ may itself change with time if the size distribution of the incoming projectiles changes. A general obliteration process, which may be the sum of several separate geological processes, may be described by two simple variables: $o(T)$, the obliteration rate (independent of crater diameter), and $a(D)$, the amount of obliteration required to remove a crater of given diameter (dependent on process but independent of time). Clearly the amount of erosion or deposition necessary to obliterate a large crater is generally more than that which will erase a small crater; thus $a(D)$ is a monotonically increasing function for most geological processes (isostatic compensation is an exception).

Equilibrium

Perhaps the crucial concept in cratering statistics is that of *equilibrium*, in which the observable crater frequencies $N(D)$ do not change with time and equal $F(D)$. Mathematically, the equilibrium frequency $F(D,T)$ at diameter D and time T can be shown (Jones 1974) to equal

$$F(D,T) = [c_t(T)/o(T)] \cdot a(D) \cdot c_d(D). \tag{1}$$

Note that, given some diameter dependence of the cratering and obliterative processes, the equilibrium frequency at any time T depends only on the ratio of rates of cratering to obliteration. (While one can always calculate an equilibrium frequency, the observed crater population $N(D)$ need not yet have attained equilibrium.)

Crater morphologies may be divided into several classes, ranging from fresh to highly degraded (see Figure 5). While craters are classified on the basis of

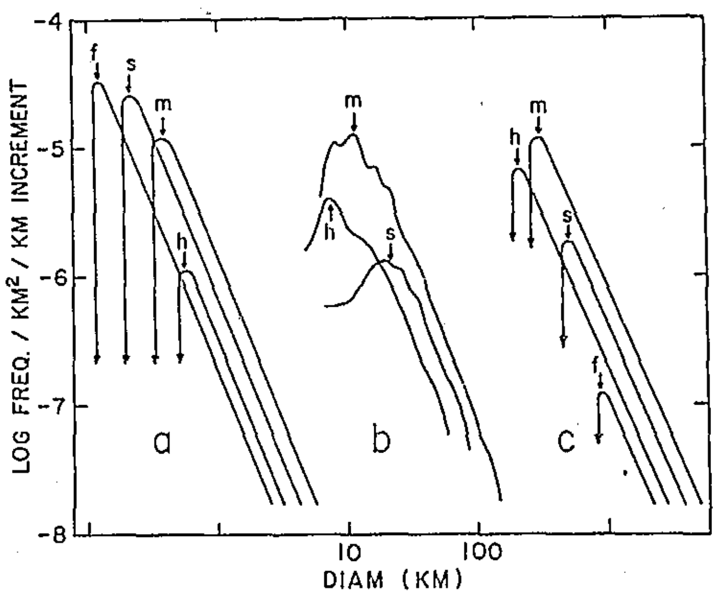

Figure 4 Diameter dependence of maxima in the frequency relations for degraded craters in Martian cu terrains are compared with two models. Curves are shown for fresh (f) craters and successively more degraded craters of classes s, m, and h. (a) The effect of observational loss of craters is due to finite resolution. Fresh craters can be observed to smaller diameters than highly degraded craters, yielding the sequence s-m-h with increasing diameter. (b) Counts of degraded craters for cratered units 29 and 32 of Jones (1974) show a sequence h-m-s, opposite to that in panel (a). (c) An equilibrium population of craters is subjected to massive obliteration. Smaller craters are obliterated altogether while the largest ones are relatively unaffected. At intermediate diameters there is the sequence of degraded craters h-m-s, similar to the observations.

Figure 5 Oblique view across the large basin, Argyre Planitia, taken by the Viking 1 Orbiter. Craters of various morphologies, ranging from fresh to highly degraded, surround the basin. South is to the upper right. NASA photo, used courtesy of Viking Orbiter Imaging Team.

morphological criteria (e.g. diameter/depth ratio, sharpness of floor features, terracing, etc), we *define* crater classes here in terms of the "amount" of obliteration $a_i(D)$ necessary to change a crater of given diameter from class i to the next more degraded class. This definition bears a clear intuitive relationship to the observational classes, independent of diameter D, provided plausible morphological criteria are used to classify craters. We employ four classes in this paper: fresh (f), slightly degraded (s), moderately degraded (m), and highly degraded (h). Clearly $a_f(D)+a_s(D)+a_m(D)+a_h(D)$ must equal $a(D)$, the total amount of obliteration that removes the crater entirely. Note that the ratio $a_i(D)/a(D)$ represents the fraction of a crater's lifetime spent in class i, if $c_t(T)/o(T)$ is constant. Given that the classes are properly defined such that $a_i(D)/a(D)$ are constant, then, in equilibrium, there are equilibrium frequencies $F_i(D, T)$ for each class i that are parallel to each other and to the total crater equilibrium curve $F(D, T)$. These are exemplified in Figure 4*b*, where it is apparent that, by our definitions of morphological classes (Arvidson, Mutch & Jones 1974), craters spend the longest part of their lifetimes in our m class (the shortest times are spent as fresh craters).

A special type of equilibrium may be established if endogenic processes are so ineffective that craters are obliterated primarily by subsequent crater impacts. This is called *saturation equilibrium* and, despite numerous studies (e.g. Gault 1970, Marcus 1970), it remains a poorly understood aspect of cratered surfaces. Saturation equilibrium results from the impossibility of fitting more than a finite number of craters into a given area without the subsequent craters destroying pre-existing ones or covering them with ejecta. Here $o(T)$ is clearly controlled by $c_t(T)$; furthermore, it is known that $a(D)$ depends on $c_d(D)$ in such a way that $F(D, T) \propto D^{-3}$ when the production function $c_d(D)$ has a constant slope steeper than -3. The constant of proportionality, which determines the height of the equilibrium frequency curve on a graph such as Figure 2, is a matter of some dispute (cf Chapman, Mosher & Simmons 1970, Marcus 1970, Woronow 1977a); it depends weakly on $c_d(D)$ and perhaps on the structural characteristics of the ground. Clearly the equilibrium frequency cannot greatly exceed that at which the cumulative area of observable craters exceeds the area in which the craters are formed. It is commonly thought that saturation equilibrium frequencies range from a few percent to perhaps 50% of a given area, for different cases.

The crater production function $c_d(D)$ is commonly represented by a power law or a combination of separate power laws over different diameter ranges. There are both observational and theoretical reasons for using power laws in some cases, but in general the diameter dependence may not be a power law, as recently emphasized by Woronow (1977b). In Figures 2 and 3 we represent production functions by power laws (straight lines on such log-log plots) for purposes of explication only; later we compare with the data.

OBLITERATION EPISODE INTERPRETATION

In order to interpret Martian cratering and obliteration history, it is useful to consider different diameter ranges separately inasmuch as the morphologies of the largest craters tend to have been shaped by the largest-scale processes that occurred in Mars' ancient history while the smallest craters have been shaped by recent processes. It is primarily from the morphologies of intermediate-sized craters that we conclude there was an obliterative episode in intermediate Martian history.

Large Craters

We consider first the population (*D* in Figure 2) of large, degraded craters which rather densely cover the cratered uplands (cu) units on Mars. The best Mariner 4, 6, and 7 pictures were primarily of cu units, which gave Mars its early, not entirely representative, "moon-like" image. We interpret the largest Martian craters to represent an equilibrium population, as concluded earlier by Chapman, Pollack & Sagan (1969) and Soderblom et al (1974), for two reasons: 1. all the cu units attain nearly identical total crater frequencies at the largest diameters (compare coincidence at large diameters of curves 1 and 2 in Figure 3); 2. there is a spectrum of crater morphologies and the frequency curves for each class roughly parallel the total crater curve (Figure 4).[2] Our interpretation is illustrated in Figure 2 by having $N(D)$ abut an equilibrium frequency curve in the vicinity of *D*. Since this early period of obliteration (prior to the event discussed below) extended to the largest craters, no remnant critical diameter is visible at large diameters. Our view differs from the Hartmann/Öpik model (note lack of coincidence of observed large craters with hypothesized equilibrium curve *B* in Figure 2) and from the more recent model of Woronow (1977b) and Strom & Whitaker (1976), in which portion *D* is interpreted as a production curve $c_d(D)$.

The degradation of the largest Martian craters may have been due to exogenic processes, endogenic processes, or both. Certainly it was assisted by the fact that the largest craters form, or shortly become, shallower in proportion to their diameters than smaller craters. As shown in Figure 1, the depth/diameter ratio even for "fresh" craters decreases towards larger sizes for the Moon, Mercury, and probably for Mars. Figure 1 may be considered for many obliteration processes (e.g. dust filling) as a plot of $a(D)$ since the crater depth is equivalent to the total relief to be eroded or buried by the process. If $a(D)$ levels off to being more nearly constant (depth ~2 km) at largest diameters, the shape of the equilibrium frequency curve would approach that of $c_d(D)$, according to Equation (1); this may explain the steep slope near *D* in Figure 2.

Although Chapman et al (1969) considered that the Martian craters were possibly in saturation equilibrium, most researchers have doubted that possibility because of their low spatial density, which is much lower than many lunar highlands crater populations. Some workers even doubt that the lunar craters are in saturation equilibrium (Woronow 1977a, Strom & Whitaker 1976, Oberbeck et al 1977). If large Martian craters really are formed with much more shallow profiles than their lunar counterparts (Figure 1), perhaps because of high volatile content of the Martian ground plus greater Martian gravity, it is possible that saturation cratering

[2] The latter observation need not imply equilibrium if, for some reason, $a(D)$ is a constant for large diameters.

could have been the sole obliterative process on Mars. More likely there was a substantial early endogenic obliterative process in addition to the cratering process itself.

Intermediate Craters

Perhaps the dominant characteristic of frequency relations for Martian cu units is the shallow segment at intermediate diameters. We believe that the shape of this feature, its variation from region to region, and the shapes of the frequency relations for the separate classes of craters are very likely due to the evolution of the crater population to a new, lower equilibrium frequency during an "obliterative event." By this we mean that the ratio $c_i(T)/o(T)$ sharply decreased, lowering $F(D, T)$ by that amount. Small craters formed during the event would abut the new equilibrium line and follow it, just as they follow equilibrium line A in the Hartmann/Öpik model in Figure 2. The "critical diameter," originally very small, evolved to larger diameters and stopped at the point indicated in Figure 2 at the end of the event. Craters somewhat larger than that critical diameter remain highly degraded today, whereas much larger craters (>50 km diameter) were hardly affected by the event.

To account for the observed population of small fresh craters, we require—as did earlier investigators—that the obliterative process cease or at least diminish to its pre-event level. The addition of the post-event craters to the sparse population of small craters degraded during the tail end of the event yields the observed relation $N(D)$, plotted as a slightly thicker line in the middle panel of Figure 2. (The little kink is smoothed somewhat by the dashed line C to account for statistical variations in the degree to which craters of a given size respond to a given obliteration process.)

As we have explained before, an equilibrium process results in frequency relations for the separate morphological classes that parallel the total crater curve. Such parallel frequencies would be predicted by the Hartmann/Öpik model near A in Figure 2 (also superimposed on the data as dotted line A' to the right). But the degraded craters on all cu units show a prominent trough, as illustrated for one region in Figure 2. This feature, if rea[illegible]equires, within the constraints of our model, that there was an epoch of [illegible]equilibrium between two equilibrium frequencies, or in other words, an obliterative event.

One might initially suppose that the depletion of degraded craters with diameters between 5 and 15 km is due to observational loss near the lower limit of usable Mariner 9 A-frame (wide-angle) resolution. However, as shown in Figure 4, the frequency relations for the separate classes refute this possibility. Clearly, if there is a limiting resolution, the deep, fresh, bowl-shaped craters will be perceived at smaller sizes than will the most degraded craters; the limiting diameter will increase from f to s to m to h (Figure 4a). But the data show precisely the opposite trend (Figure 4b), which is difficult to explain by resolution effects alone yet is easily explained by obliteration. Figure 4c shows schematically what happens if an equilibrium population of craters is suddenly blanketed, for example, by a layer of dust. Some initially fresh or only slightly degraded craters of small diameters are still visible now as highly degraded craters, whereas the only craters remaining fresh are those so large as to be unaffected by the blanketing. The resulting curves look very similar to the actual data in Figure 4*b*, emphasizing the plausibility that an obliterative episode would have yielded the observed crater populations.

Frequency relations for the cratered uplands are not identical for all regions. It is noteworthy, however, that they differ in ways that are entirely consistent with an obliteration event. The event must merely have been stronger in some regions than in others. For instance, for total crater populations in two different regions (Figure 3), the kink in curve 1 occurs at a smaller diameter than in curve 2, suggesting that the regions represented by curve 1 suffered less obliteration during the event than those of curve 2. Furthermore, in all cu regions, the diagnostic ordering (*h-m-s*) of the maxima in Figure 4*b* is preserved, even though the ensemble is shifted depending on the magnitude of the event. While curves 1 and 2 in Figure 3 are separated substantially near diameters of 15 km, they are nearly coincident at diameters of 3 km with frequencies very similar to frequencies for the cratered plains (pc); apparently the pc plains were formed contemporaneously with the end of the obliteration event.

There is an interesting question that could be resolved if we had good counts of craters with diameters of 1 to 3 km: was the obliteration event more effective in some areas because it lasted longer or was it simply more intense? Case 1 in Figure 3 shows theoretical frequency relations for two different regions suffering different obliteration rates for the same duration, while Case 2 shows two regions suffering the same rates for different durations. The chief difference between the two cases is that the 1 to 3 km frequencies are different for the two regions in Case 1 but the same in Case 2. The data *seem* to resemble Case 1, but a definitive result must await analysis of statistically large samples of 1–3 km craters from Viking photographs.

Small Craters

Virtually all Martian craters smaller than a few kilometers in diameter must have formed relatively recently—just at the end of the obliterative event or later. Older small craters would certainly have been totally obliterated by the processes that so greatly modified the intermediate diameter craters. Of course, the freshness of the small craters means that the degradation rate has been very low since the event. Yet the presence of planet-wide duststorms suggests that *some* erosion and deposition must be continuing. If so, there is an equilibrium frequency that must be attained at *some* small diameter, given the apparent steepness of the production function $c_d(D)$.

The present equilibrium frequency would be evidenced by a bend in slope near a "critical diameter" analogous to that for larger craters in the Hartmann/Öpik model. Crater counts from some narrow-angle Mariner 9 pictures (B frames) do not clearly reveal such a critical diameter, although Chapman (1976a) found a range of degraded crater morphologies at diameters of several hundred meters and smaller, suggesting the onset of obliteration near the lower resolution limit of the frames. This corresponds to a surprisingly slow rate of obliteration, equivalent to a depth of erosion or deposition of the order of 10 m since the end of the obliterative episode. Preliminary studies of B frames by several other investigators suggest a somewhat larger rate of post-event obliteration in some selected cu units. Viking Orbiter pictures have emphasized the widespread distribution of secondary craters (Carr et al 1976); if the small, degraded craters studied by Chapman and others were really secondaries, then the post-event rate of net obliteration has been even less than they inferred.

Summary

Our model for Martian cratering and obliteration is relatively simple and satisfies the data extremely well. That it is a unique solution is more difficult to prove. Our scenario is this: Mars was bombarded by an early rain of projectiles, cratering the uplands units. A large-scale, efficient obliteration process acted contemporaneously with the cratering; it may have been the cratering process itself acting upon abnormally shallow "fresh" Martian craters. More likely there were atmospheric or other endogenic obliterative processes operating as well.

Later, the rate of obliteration increased dramatically with respect to the cratering rate, obliterating craters smaller than 10 km in diameter and modifying those somewhat larger. The high obliteration rate was sufficiently brief that its cumulative effect was insufficient to modify the largest craters. The obliterative episode was more effective in some regions than others, probably because of different obliterative rates, but possibly due to different durations. One might speculate that the episode happened at a time when internally generated heat reached a maximum near the surface of Mars, perhaps generating a thick atmosphere (see Conclusion section below). Whatever the nature of the obliteration, it ceased more or less coincidently with the emplacement of the pc units, which were perhaps due to volcanism associated with the same hypothetical thermal maximum.

During subsequent ages, while portions of the northern plains and the Tharsis Ridge have been resurfaced by volcanic and/or local aeolian or fluvial deposition, the older units (cu and pc) have been subjected to very little erosion.

ALTERNATIVE INTERPRETATIONS OF MARTIAN CRATERING

Soderblom et al (1974) interpreted the Martian cratering record as implying a simultaneity between cratering and obliteration. Our own models (Jones 1974, Chapman 1974a), depicting an obliterative episode occurring *after* the episode of heavy bombardment, might seem incompatible with Soderblom et al, but the models differ only in emphasis. Soderblom et al emphasized the larger Martian craters—a population that we agree evidences a probable equilibrium spectrum of crater morphologies. We have chosen to emphasize the smaller-scale obliterative episode that we believe occurred in intermediate Martian history because of the evidence for its presence and for its possible temporal association with other important geological events on Mars: the aqueous furrowing of the equatorial cu units and the formation of the first extensive plains units remaining today, the pc units. Soderblom et al did not dispute such variations in the ratio of obliteration to cratering rates.

There is a tendency for planetary geologists to avoid "catastrophist" interpretations of planetary histories, so the association of cratering and obliteration rates has seemed more acceptable than some extreme versions of our obliterative event, such as Jones' (1974) suggestion of the possibility that the event might have been an obliterative "spike" in very recent Martian history. We now see little reason to regard the episode in such stark terms; the problem of absolute chronologies is discussed below.

The major alternative models for Martian cratering have been spurred by Mariner 10 and the resulting studies comparing the cratering on Mercury with that on the Moon and Mars. Some fundamental underpinnings of Martian cratering theory are now being questioned. A common thread to the alternatives is that the production function $c_d(D)$ of primary craters differed substantially from the commonly assumed power law, at least during some early epochs.

Studies of the relationships between plains units and cratered units on Mercury and the Moon have led Oberbeck et al (1977) to suggest that $c_d(D)$ was deficient in craters with diameters smaller than 40 km. There is an obvious paucity of such craters on Mercury (Guest & Gault 1976). Oberbeck et al suggest that a similar deficiency exists on the Moon, but is partly masked by the presence of large secondary craters from the basin-forming events. Such basin secondaries are less evident on Mercury because Mercury has fewer basins and because higher Mercurian gravity would constrain such secondaries to the immediate peripheries of the basins (Gault et al 1975). Wilhelms (1976) has independently suggested that many of the larger lunar craters are actually basin secondaries.

If these interpretations are correct, it is reasonable to suppose that $c_d(D)$ for Mars was also deficient in craters less than 40 km in diameter. One current hypothesis (Murray et al 1975) is that all three planets were struck by the same population of projectiles at the same epoch. In fact, Wetherill (1975) has proposed a reasonable scenario for the tidal fragmentation of a large object crossing the orbits of Earth or Venus that would have resulted in a bombardment episode on all of the terrestrial planets. Such a scenario satisfies the interpretations of some researchers (e.g. Tera, Papanastassiou & Wasserburg 1974) that lunar rock-age distributions require a cataclysmic bombardment of the Moon about 4 b.y. ago. Chapman (1976b) offered another version of Wetherill's scenario, involving the collisional fragmentation of a large object in the asteroid belt. If the fragmentation was really tidal, rather than collisional, then the projectile population might well have been dominated by larger bodies and "deficient" in smaller ones.

One need not necessarily accept the cataclysm scenario nor an association between Martian, lunar, and Mercurian cratering in order to hypothesize that $c_d(D)$ for Mars was deficient, relative to a power law, in the sub-40-km range. While collisional fragmentation is usually thought to yield power-law size distributions, the early cratering projectiles need not have been a highly evolved collisional population.

Oberbeck et al have emphasized that tidal stress on very weak incoming projectiles could break them into a cluster, thereby yielding the hypothesized curved $c_0(D)$; such effects would differ for the Moon, Mars, and Mercury.

Strom & Whitaker (1976) have also proposed that the relative absence of smaller craters on the Moon, Mercury, and Mars is characteristic of the production function of an early but now extinct population of impactors rather than due to the effects of obliteration. They emphasize that their suggestion is bolstered by the claims of Woronow (1977a) that the spatial density of craters on even the most heavily cratered regions of the Moon is too low to be accounted for by saturation equilibrium. Woronow's Monte Carlo simulation of saturation cratering reached equilibrium at densities several times higher than observed on the Moon. His model, however, fails to employ a sufficiently large diameter range and is quite elementary. A crater is represented by four points on a virtual surface and the crater ejecta blanket is modelled to remove craters within its limits with 100% effectiveness while not affecting even small craters exterior to it at all.

Moreover, Woronow's simulation fails to match Gault's (1970) physical simulation of saturation cratering; his criticisms of Gault's procedures seem inadequate to account for the discrepancies. Gault's experiments, however, concerned production functions with steep slopes; in the shallower-slope regime, which may be more relevant to the large craters discussed here, the inadequacies of Woronow's simulation may be less serious.

The strongest part of Strom & Whitaker's case is their observation that fresh lunar craters on the Mare Orientale ejecta blanket display a curving $N(D)$ that is deficient in smaller craters and similar in shape to frequency curves displayed by highlands craters. The significance of this observation is that Orientale craters are widely separated and all of reasonably fresh morphology, so they cannot be in equilibrium with saturation cratering nor can they have been affected much by any other lunar obliterative process. Strom & Whitaker suggest that the Orientale craters sample the tail end of cratering by the population responsible for most lunar, Martian, and Mercurian craters. (The *post*-mare lunar craters, as well as plains unit craters on Mars, follow much more nearly a power-law distribution, such as that illustrated for fresh craters in the right-hand side of Figure 2.)

Despite similarities, the models of Oberbeck et al and Strom & Whitaker are partly incompatible. In particular, many of the Orientale ejecta blanket craters counted by Strom & Whitaker are deemed to be Orientale secondaries by Wilhelms (1976), and Oberbeck et al also consider the formation of large secondaries to be important. Strom & Whitaker generally argue for relatively modest influence of basin formation on lunar crater populations, whereas Oberbeck et al regard the effects as pervasive across the lunar frontside, with only a few areas relatively unscathed.

Since these alternative models have been developed chiefly in a lunar and Mercurian context, serious discussions of the implications for Mars have not yet appeared in the literature. We perceive a number of potential difficulties with these hypotheses, however. First, it seems unlikely that all 20- to 30-km craters formed on Mars could remain intact while much larger craters are so highly degraded. It would require a function $a(D)$ very nearly constant from diameters of twenty through several hundred km; that is, one must assume that it is no more difficult to erode or obliterate a 200-km crater than a 20-km crater. While the diameter-depth data do not yet exclude such a possibility for Mars, it would be a most peculiar geological process that would behave in such a fashion if fresh Martian craters bore any resemblance to their lunar or Mercurian counterparts (Figure 1).

A second difficulty is that it is not possible to regard the data shown in Figure 3 as compatible with a single production function; curve 1 is not a simple multiple of curve 2. It is possible to make the ad hoc assumption that the more heavily cratered terrains (curve 1) were struck by a population less deficient in small bodies than moderately cratered terrains (curve 2) in just the proportions that would mimic the behavior of an obliterative episode of variable strength. However, this assumption is not persuasive.

One might argue that curve 1 in Figure 3 is a production function and that curve 2 represents the same population modified slightly by obliteration. But obliteration necessarily modifies crater morphologies, which brings us to a final question, yet to be addressed in the alternative models: Why should a curving production function of craters in the 10- to 30-km diameter range manifest the unusual distribution of morphological classes, shown in Figure 4, that seem so reasonably explained by an obliterative episode? The general question of what processes have been responsible for the degraded appearances of most lunar, Mercurian, and—especially—Martian craters is a matter of great importance for making the proposed alternatives convincing. The question is particularly relevant to Strom & Whitaker; Oberbeck et al at least believe that substantial obliteration accompanied emplacement of basin ejecta [Hartmann & Wood (1971) and Chapman (1974a) interpreted lunar crater frequencies in terms of basin ejecta blanketing].

To summarize, we believe our own model for Martian cratering and obliteration (previous section) well accounts for the data. We cannot assert that the interpretation is unique, however, especially in the face of the fundamental challenge to the long-accepted belief that the lunar upland craters represent a saturation equilibrium population. However, quite apart from debates concerning the plausibility that craters 30 km in diameter can be basin secondaries, the recent models require further development to see if they can prove to be as successful as ours in describing the observed populations of craters of different morphological classes and the variations in those distributions from place to place on Mars.

ABSOLUTE CHRONOLOGY

There is no known way to determine the absolute age (in years) of a geological unit on another planet in the absence of (*a*) datable rocks or (*b*) a well-calibrated relationship between cratering flux and crater density. For Mars, of course, we lack datable rocks, so we must rely on the principles of crater-count age-dating first described in detail by Shoemaker, Hackman & Eggleton (1962). In order to find the age of a unit from its crater density one must know the cumulative cratering flux as a function of time.

Figure 6 shows the calibration diagram for Mars. The first widely used Martian chronology was that of Hartmann (1973), which was based on the uncertain hypothesis that the crater-production rate on Mars has been six times that on the Moon (the absolute chronology can then be calculated since the lunar chronology is known, from dated moonrocks). It is now thought that the crater-production rates on the two planets are probably more nearly equal. Soderblom et al (1974) attempted to derive the Martian cratering rate without adopting a particular multiple of the lunar rate. But their calibration curve involved the *assumption* that Martian surface-forming processes occur at a uniform rate – a uniformitarian assumption based on a plausible, but unproven, analogy with the Moon. Murray et al (1975) proposed that the crater-production rates on the Moon, Mars, and Mercury are rather closely equal; that assumption produces a curve on Figure 6 close to Soderblom's, but below it.

The firmest basis for estimating relative cratering rates on the terrestrial planets comes from an inventory of existing small-body populations in the inner solar system and calculations of their subsequent orbital evolution, in particular their collision probabilities with planets. Wetherill (1975, 1976) has emphasized the similarity of the crater production rates on terrestrial bodies, but he does not strongly dispute Chapman's (1976b) assertion that these rates may be uncertain over a range of up to an order of magnitude, especially for Mars. Chapman (1976b) considered the present status of our knowledge of cratering fluxes [based mainly on calculations by Wetherill (1975) and Hartmann (1977)] and proposed two extremes for Mars (shown as alternatives 1 and 2 on Figure 6). None of the cratering rates shown in Figure 6 are sufficient to produce all the observed craters on the cu units in 4.5 b.y. Accordingly there must have been a period of higher flux; most plausibly this occurred ~4 b.y. ago, as on the Moon, but the hypothesis is unproven.

The pc (cratered plains) units are adopted as the standard for comparison of crater densities in Figure 6. These include the eastern part of Solis Planum, Lunae Planum, and Syrtis Major Planitia and appear to be the oldest of the plains units inasmuch as they have small-crater densities comparable to those of the cu units,

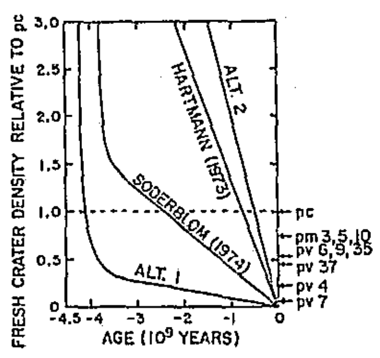

Figure 6 Correlation between small-crater density and age for a variety of cratering fluxes. Crater densities are plotted for a variety of plains units, taken from the data of Jones (1974).

which date the end of the obliterative event. Younger units may be dated from the densities of craters 4 to 10 km in diameter (indicated at the right of Figure 6). The second oldest regions shown in Figure 6 are pm-10, pv-3, and pv-5, which include regions west of Solis Planum. Still younger, with roughly half the pc crater density, are the volcanic plains units pv-6, pv-9, pv-35, and pv-37, which include much of Elysium Planitia and units north of the Tharsis ridge. Plains south-west of Arsia Mons (pv-4) are much younger still and the area surrounding the Tharsis Montes are youngest of all major units for which Jones (1974) tabulated crater frequencies. (The abbreviations cu, pc, pm, etc employed here are for units defined and mapped by Mutch & Head 1975.)

It is clear that the crater densities cannot be translated into ages even as vague as "a couple of billion years" if one agrees that alternatives 1 and 2 provide a reasonable range for the cratering flux on Mars. Elysium Planitia may be only a few hundred million years old, but it might instead date from the tail end of an early bombardment. Of course, presentation of such a broad range of ages for particular features does not adequately convey the rather precise degree to which we can determine the *relative* ages of features. Thus we think that a better way to refer to ages of Martian units is in terms of crater densities relative to the pc units. Attempts to specify ages in years should be avoided until the chronology is better determined.

GEOMORPHOLOGICAL PROCESSES

What we call "the obliterative process" must represent the cumulative effects of innumerable different geological processes. They can be modelled as a single average process for large statistical samples of craters. But verification that our generalization is valid depends upon explicit analyses of separate processes, including detailed photogeological interpretation of specific features.

The literature contains many papers about specific geomorphological processes, mostly based on photogeological interpretation or analogies with familiar terrestrial processes. Some studies, especially of aeolian processes, have included windtunnel experiments and theoretical treatments. It would be premature to treat all of this literature here, since few of the studies have been integrated with the others or applied to a global Martian synthesis. Some recent papers are mentioned below as an introduction to the literature.

Some geomorphological processes are much more general and widespread in their effects than others. Rock sliding and channelcutting may have devastating effects on landforms in certain localities, but such processes of local origins do not substantially affect widespread Martian units. On the other hand, atmospheric processes such as rainfall or aeolian deposition can extend over the entire planet. Perhaps the nonexogenic, nonatmospheric process of greatest potential extent is volcanism; lava flows may spread across vast areas and an epoch of heating causing the permafrost to melt could envelop much of the planet, having similar effects on topography on opposite sides of Mars. Clearly, the processes responsible for most of the crater obliteration discussed in this article have been of the widespread variety.

Exogenic Processes

Destruction of pre-existing topography by the cratering process itself has been extensively studied (see earlier discussion of saturation equilibrium). It had been thought that the planet Mercury provided the most reasonable model for fresh cratering on Mars because of the similarity in gravity on the two planets (Gault et al 1975). However, ejecta blanket morphologies and secondary crater distributions on Mars appear to differ from those on either the Moon or Mercury, suggesting that, at least in certain localities, the atmosphere and/or underground ice deposits have substantially altered the effects of crater formation on nearby topography (Carr et al 1976).

Aeolian Processes

The wind modifies features on Mars in two chief ways: erosion by abrasion or plucking and transport of fine materials by saltation or suspension from one location to another. There is abundant evidence in Mariner 9 and Viking pictures for the local importance of aeolian processes on Mars, including dune fields. McCauley & Grolier (1976) have studied yardangs in the driest terrestrial deserts as analogs of "inverted ship" shaped features on Mars. Scarp recession and formation of pedestal craters also have been ascribed to the wind (King & Riehle 1974, Arvidson et al 1976, and others). There can be no question that dust is moved about on Mars by wind. But inasmuch as we have very little experience on Earth with large-scale terrain that has been affected more by wind than by water, it is uncertain to what degree some of the large-scale Martian features truly are of aeolian origin. Useful studies of Martian aeolian processes and the erosion rate in particular have involved combinations of experimental and theoretical approaches (cf Greeley et al 1974, Sagan & Bagnold 1975, and Iversen et al 1975). Some researchers have calculated surprisingly rapid erosion rates, at least for lateral erosion (e.g. scarp recession) as opposed to deflation.

Many units on Mars have been interpreted as being modified by aeolian deposition. In particular, Soderblom et al (1974) have mapped extensive "dust mantles" poleward of 40° latitude parallels. There can be little doubt that dust deposition has been important in producing layered deposits in polar latitudes. But it remains for Viking Orbiter analysis to determine the extent to which units mapped as dust mantles may in fact reflect poor resolution or lingering atmospheric dust during the Mariner 9 photography.

Aqueous Processes

The flow of liquid water appears to have played a major role in shaping the surface of Mars. First recognized in Mariner 9 photography (Milton 1973), the evidence for fluvial processes has become overwhelming in Viking Orbiter photography (Carr et al 1976). Most striking are the large channels, which are especially prominent near the boundary that separates the cratered and uncratered hemispheres from each other. The first Viking Orbiter pictures showed impressive views of such channels emerging from the chaotic terrains of Mariner 6 and from the canyonlands of Mariner 9, emptying into the Chryse basin where the first Viking landed. While these large channels have been classified into several different types, a common hypothesis is that most large channels were carved by great floods of water derived from ice deposits in the ground. The closest terrestrial analogy may be the channeled scablands of eastern Washington, where catastrophic flooding occurred when the waters of Lake Missoula evidently broke through an ice dam (Baker & Milton 1974).

Still more interesting fluvial evidence is afforded by the "furrows," which are smaller stream and river valleys in the cratered terrains, possibly confined to equatorial and temperate latitudes. While some furrow systems are poorly integrated, there are many well-developed dendritic patterns of great areal extent, implying origin of the waters from widely dispersed areas—most likely by rain (cf Pieri 1976). It is tempting to associate the formation of furrows with the obliterative event we have described. Certainly, the tiny observable furrows could not have been formed prior to the last stages of the event; otherwise they would have been obliterated. But they do not exist on the pc units formed just after the event. Thus they are temporally associated with the episode. Rainfall is certainly known to be a highly effective erosive agent on Earth, so it might well have yielded the high obliteration rate required by the low equilibrium frequencies during the Martian obliterative event.

Other Processes

Volcanism has caused much modification of topography on Mars. It is primarily a constructional process, either laying down vast plains of lava or ash or building giant shields such as Olympus Mons. Carr (1974), however, has discussed some situations in which lava is actually erosive, and he has attributed the origin of some lunar-rille-like channels on Mars to erosive volcanic processes.

There are many tectonic processes that modify the Martian surface. These include the formation of grabens, faults, and fractures due to internal stresses, such as those associated with the comparatively recent formation of the Tharsis uplift. Schultz (1976) has studied explicitly the so-called floor-fractured craters. There are also numerous local processes, including landslides, mudslides, and less spectacular processes of downslope movement that reduce topographic relief on Mars (an example is discussed by Veverka & Liang 1975).

Scarp recession has been the major process of dissecting the fretted terrains and removing many other apparently sedimentary sequences on Mars. Whether the actual erosive agent is mainly windblown particles, as commonly assumed, beach erosion by bodies of water, or slumping due to failure of subsurface ice is not always clear. But the removal of unconsolidated layers often reveals previous topographic horizons. Figure 7 shows a once-buried crater being exhumed as a scarp retreats across it. If processes of exhumation were widespread, our earlier assumption of the one-way direction of crater degradation would be violated.

On Mars, as on the Earth, erosion and deposition cannot be considered independent of physical and chemical weathering processes that render particles subject to fluvial, aeolian, or mass-wasting transport. An early suggestion (Chapman, Pollack & Sagan 1969) was that the particulates were derived by comminution in cratering impacts. Other processes of weathering have been addressed in other contexts (Malin 1974, Siever 1974, Huguenin 1974, 1976).

CONCLUSION: THE GEOMORPHOLOGICAL EVOLUTION OF MARS

Mars accreted as a planet with substantial volatile content (cf Fanale 1976). The evolution of these volatiles, governed by the internal and external thermal budget of the planet, is evidenced by the cratering record. We have already described the early bombardment of Mars and the probably contemporaneous obliteration process, which was possibly due to saturation cratering alone but was more likely of endogenic origin. Probably Mars had a substantial atmosphere during these early epochs.

Upon losing any accretional heat it may have had, the surface of Mars became very cold. Whatever water vapor was not lost to space must have rapidly condensed onto, and percolated into, the ground and frozen. The evidence for an obliterative episode that affected mid-sized craters (perhaps associated with the furrowing) suggests that the volatiles were released again. Getting water out again onto the surface of Mars in order to form individual large channels requires a subsequent period of heating, perhaps by local volcanic hot spots. But getting water into the

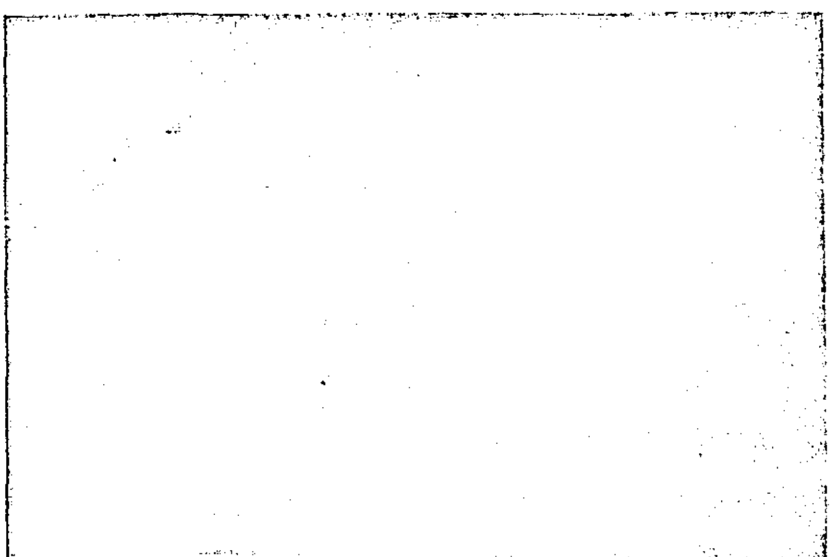

Figure 7 Mariner 9 picture of a crater in the Kasei Vallis region apparently being exhumed from beneath a receding cliff. NASA photograph.

atmosphere, in order to rain and produce dendritic patterns over much of the planet, requires planet-wide reheating of the surface (plus a sufficient amount of available water). That is necessary in order to elevate the temperature of the coldest spot on the planet so that the vapor pressure of water at that spot exceeds the partial pressure of water in the whole atmosphere (Mutch et al 1976). Otherwise any released water would be rapidly (a few years or less) frozen out at the polar cold-traps, which is a problem with some of the heating models based on enhanced solar luminosity (Hartmann 1974a) or cyclical insolation variations associated with obliquity changes (Ward 1973). (The reasoning does not apply to the Earth, because of our planet's superabundance of water, which obviously cannot all be frozen out at the poles.) Planet-wide elevation of surface temperatures on Mars cannot be accomplished by any reasonable level of endogenic heating. An atmospheric greenhouse effect seems required, perhaps assisted by higher polar temperatures associated with the larger pre-Tharsis obliquities of Mars hypothesized by Burns, Ward & Toon (1977). A period of volcanic activity and crustal heating may have supplied once-frozen underground water to the atmosphere, triggering a rainy spell.

The geological record on Mars provides possible independent evidence for a thermal maximum in crustal temperatures roughly contemporaneous with the obliterative event. The formation of the major volcanic units visible today commenced with the pc units shortly after the end of the event and has continued, at least near Tharsis, practically to the present day. Thus the onset of major Martian volcanism may have been due to the same planet-wide crustal heating (a radiogenic heat pulse) that led to the generation of a moist Martian atmosphere, producing the obliterative event.

This plausible scenario is only a suggestion. There is evidence for some ancient volcanism on Mars, and Wilhelms (1974) has suspected that it was pervasive; it may even have been a major obliterative process. On the other hand, the northern plains units need not be chiefly volcanic; many may result from aeolian deposition or even sedimentation from fluvial outwash and shallow seas. So the predominance of fresh volcanism on Mars may just reflect the lack of recent obliteration. Thus there may be no temporal association between the thermal evolution of Mars and evolution of its atmosphere. The aqueous period might not even have required new outgassing of water; the rain could have resulted from condensation of water upon cooling of the original atmosphere formed concurrently with accretion.

Nothing in the Martian cratering record requires cyclical variations in climate, such as those that Sagan (1971), Sagan, Toon & Gierasch (1973), and Sagan & Lederberg (1976) have postulated might from time to time provide more clement conditions for organisms "in cryptobiotic repose awaiting the return of wetter and warmer conditions." The polar laminated terrains (Cutts 1973) and evidence that channels flowed more than once (Hartmann 1974b) indicate discontinuous processes, but evidence of anything approaching sinusoidal oscillation is absent. Theoretical calculations (Ward 1973) of cyclical atmospheric evolution yield timescales far too short (e.g. 10^6 years) to be measured by the cratering record, given our present knowledge of the absolute cratering chronology and the slow rates of geological processes evident on Mars today. Instead, the last observable planet-wide crater-obliterative event seems to have occurred prior to half a billion years ago, and perhaps as early as the tail end of the early bombardment period on Mars.

ACKNOWLEDGMENTS

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APPENDIX 3

"The Collisional Evolution of Asteroid Compositional Classes"

by

D. R. Davis and C. R. Chapman

THE COLLISIONAL EVOLUTION OF ASTEROID COMPOSITIONAL CLASSES,
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Previous studies of asteroid collisional evolution (1) have shown that the present-day belt could result from many initial populations including those much more massive than the currently observed distribution. Based on the interpretation of Chapman (2) that S objects are the exposed cores of fragmented parent bodies, it was argued that the original best was substantially more populous (by a factor of ~300 at ~100 km diameter) than the presently observed belt; however, the number of large Ceres-sized bodies was found never to have been substantially greater than it is today. Since these early studies there has been a considerable increase in the observational data on the asteroid size frequency distribution. This additional data has led to: (i) improved definition of the size frequency distribution as a function of compositional class, i.e., for carbonaceous C types, silicaceous S types, and for metal-rich M types; and (ii) an extension of the distributions to smaller diameters. In a recent review paper Zellner and Bowell (3) give a bias-corrected C population down to 50 km diameter and a combined S & M population to 25 km. This paper discusses some implications of these further observations on the collision evolution models and presents further results based on an improved and expanded model of the collisional evolution of the asteroid belt.

The observed small diameter slope of the C population (Figure 1) is less steep than previously believed; an observation which was quite difficult to interpret based on our earlier computer models which almost invariably yielded steeper slopes for the small diameter size frequency distribution than is observed. This result was obtained from a wide variety of initial conditions and values of evolution parameters. An improved model for the physics of the catastrophic fragmentation process lead to an immediate resolution of this difficulty. A key parameter in collisional evolution is the size of the largest fragment M_ℓ resulting from a catastrophic collision. The largest fragment is calculated based upon the dominant cohesive force binding the body. If mechanical strength is largest, then the largest fragment is found using the kinetic energy/gram involved in the collision and is scaled from laboratory results of Gault and Wedekind (4) and Hartmann (5). If the gravitational binding energy is dominant, then for every catastrophic collision there will be other less energetic collisions that are capable of rupturing the mechanical bonds yet have insufficient energy to disperse the fragments, i.e., a process akin to the formation of an extensive megaregolith. In this case when a catastrophic collision eventually occurs the largest fragment will contain only a small fraction of the original mass. When the two cohesive energies are comparable in magnitude an average of the two extreme models is adopted in our model.

Figure 1 illustrates the collisional evolution over 4.4 b.y. from a large initial input distribution of C-type objects. The evolved distribution now displays characteristics of the observed distribution, namely the shallow small diameter slope and the formation of a "bump" in the size frequency distribution. The "bump" develops at the size where collisions become relatively frequent and the thoroughly fractured fragments are distributed at considerably

COLLISIONAL EVOLUTION

Davis, D. R., and Chapman, C. R.

smaller sizes. However, there are not sufficiently frequent collisions at larger sizes to replenish the depleted population in this intermediate size range. The collisional strength of bodies appears to be a basic parameter in determining the collisional evolution of the population. The results illustrated in Figure 1 are only obtained using material strengths characteristic of weak substances, while strengths comparable to that of terrestrial rocks tend to result in steeper small size slopes.

Our numerical simulation was further extended to include the collisional evolution of a two-component system, i.e., a system containing two subpopulations having different physical properties which is collisionally evolving. This program was developed to investigate the mutual effects of C- and S-type objects and to determine if a small population of very strong S (or M) bodies significantly alters the C population. The initial S population was assumed to be a "bump" at a preferred size rather than a power-law distribution in order to simulate their formation as the iron cores of differentiated parent bodies; various initial distributions were input for the C population. It is found that the S population quickly develops a fragmental tail which is similar to the observed size distribution. The assumed greater strength of S-type objects precludes extensive evolution of the S objects unless very populous initial distributions of C types are involved. The S population is rather effective in fragmenting C objects, particularly if the ratio of strengths of S to C is very large, i.e., $\sim 10^4$. Initial C populations become thoroughly reduced and fall below the S population at diameters of several tens of kilometers, a result which is precluded by observations. It is characteristic of most cases that at small diameters the S population has a steeper slope than does the C population which results from the greater strength of S objects. If this trend continues to even smaller diameters than are considered in our simulations, the S population would become dominant below a certain "threshold" diameter. Also, the overall asteroid population would have a steeper slope below this threshold value, a result which is supported by results of the Palomar-Leiden Survey (6). See also (7).

In summary, our revised collisional evolution model shows that many initial populations do collisionally evolve to the current belt provided there are many collisions with the largest fragments containing <25% of the original mass. Two mechanisms are suggested for such complete fragmentation: (a) highly energetic collision when mechanical strength is important and (b) large-scale fracturing when gravitational binding energy is dominant. It must be admitted that the relatively simple collisional history that seemed implied by the earlier size-frequency data in (8), which was developed in the article by Chapman (9), can no longer be regarded as correct. While our present models show that the new data can in some cases be reconciled with a model employing many of the main elements of the earlier interpretation (e.g. S-type objects as high-strength metallic cores and the asteroid belt as a remnant of a larger early population), it is now clear that much more work is necessary to determine the probable collisional history of the asteroids.

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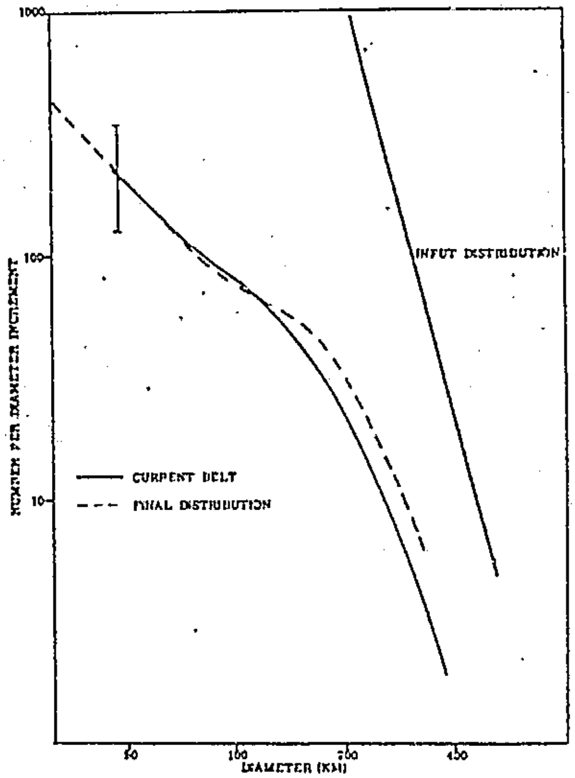

Figure 1. Collisional evolution over 4.4 b.y. of an initial population of C objects substantially more populous than the present belt at intermediate and small sizes. The diameter increment is 0.1 in log diameter and the error bar shows the estimated uncertainty in the current belt at 50 km diameter.

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APPENDIX 4

"Asteroid Fragmentation Processes and Collisional Evolution"

by

Clark R. Chapman, Donald R. Davis, and Richard Greenberg

Asteroid Fragmentation Processes and Collisional Evolution. Clark R. Chapman, Donald R. Davis, and Richard Greenberg, Planetary Science Institute, 2030 E. Speedway, Tucson, AZ, 85719

The asteroids and their fragments are a population of objects in the inner solar system, concentrated between 2 and 4 AU from the sun, which are the remnants of a much larger population of planetesimals that formed the terrestrial planets. Since a large planet failed to form in the asteroid belt, the asteroidal planetesimals have remained to collide with each other and with other planets. The smaller fragments which strike the Earth are called meteorites; the larger ones form craters. Astronomical data obtained during the 1970's have yielded some knowledge about asteroid compositions and, in particular, have strengthened the above hypotheses. These data also have permitted, for the first time, accurate estimates of asteroid sizes. These constraints on asteroid compositions and the new knowledge of asteroid sizes, combined with a knowledge of asteroid orbits and fragmentational physics, permit us to calculate asteroid collision probabilities and the evolution of the size distribution.

Chapman and Davis (1) reported results based on a preliminary computer model of asteroidal fragmentation which demonstrated that asteroids are colliding much more frequently than had been believed before -- sufficiently frequently, in fact, that the asteroids may be regarded as a remnant of a possibly much larger population of objects <u>in the asteroid zone</u>. Further discussion of collisions by Chapman (2,3) developed the hypothesis that one observational type of asteroid (designated "S") are the stony-iron cores of differentiated parent-bodies whose rocky mantles have been stripped away by numerous collisions and that another observational type (designated "C") are the highly fragmented remnant of a vast population of carbonaceous asteroids. Based on this hypothesis, Chapman and Davis (1) estimated that, in fact, the C-type asteroids were roughly 300 times more numerous at an early epoch.

Such models for the collisional evolution of the asteroids seemed to satisfy the available data about the size-frequency distributions of asteroids of the separate compositional classes (4): a power-law distribution for C-type asteroids and a more complicated distribution for S types. More recent data on asteroid size distributions by Zellner and Bowell (5) differ from the earlier data and it is clear that the simple collisional models require revision.

We have augmented our collisional model in several ways to render it more closely representative of actual fragmentational physics. First, our program has been modified to permit the simultaneous collisional interaction of two distinct compositional types, represented by material strengths deemed appropriate for the two predominant types of asteroids (S and C). We have considered cases for strengths close to nominal values for metallic iron (20000 bars) and for carbonaceous meteorites (3 bars), as well as very different values. The second major change is an improved consideration of the size of the largest fragment resulting from a catastrophic fragmentation of an object sufficiently large so that the gravitational binding energy of the object dominates the material strength.

The largest fragment from a catastrophic collision clearly depends on the energy density imparted to the target body. Because of the power-law dependence of the asteroid size distribution, most catastrophic fragmentations (in the absence of a gravity field) involve a collision imparting only marginally enough energy to overcome the material strength of the target; thus the largest fragment is usually a significant fraction of the mass of the target. But for a weak body large enough to possess an appreciable gravitational field, collisions involving sufficient energy to fragment the body will not in general be sufficient to impart the kinetic energy to the fragments necessary to overcome the body's self-gravity and to disperse the fragments. Thus a catastrophic fragmentation and dispersal of fragments must result from a superenergetic collision, which will certainly fragment the target into many small pieces. The effect will be enhanced by the fact that in general the target body will have been internally fractured by numerous collisions sufficient for fragmentation but insufficient for dispersal. Our improved collisional model incorporates these features.

Numerical experiments simulating the collisional interaction of only weak carbonaceous bodies now yield a size distribution similar to that observed (for diameters greater than 50 km) by Zellner and Bowell (5). In particular, the observed relative absence of 50 - 100 km diameter bodies appears to be due to the infrequent creation of fragments of that size by the catastrophic fragmentation of somewhat larger, gravitationally bound C asteroids.

Numerical experiments simulating the collisional evolution of strong S objects plus weak C objects demonstrate that S objects are surprisingly effective at decimating any population of C objects. Evidently S objects cannot be as strong as 20000 bars; otherwise there would not be so many C asteroids as exist. The observed size distributions of asteroids are best satisfied by simulations in which the S asteroids are not more than two orders of magnitude stronger then C asteroids. However, no simulation has yet been completely successful in producing the current distribution of both C- and S-type objects. Our numerical simulations are being further refined to include the effects of collisional erosion on the size distribution and the mutual effects of size distribution and characteristic impact velocity.

The earlier conclusions of Chapman and Davis (1) that the C asteroids may be a remnant of a much more populous asteroid belt are unchanged by these new considerations. But their argument that the belt was roughly 300 times more populous in the past depends on suppositions about the physical nature of the S-type asteroids which seem to require revision.

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APPENDIX 5

"Report on Paper presented at PGPPI Meeting

in St. Louis, May 1977"

Report on Paper presented at PGPPI Meeting in St. Louis, May 1977.
"Asteroid Fragmentation Processes and Collisional Evolution" by
C.R. Chapman, D.R. Davis, and R. Greenberg, Planetary Science Institute, Tucson, AZ 85719.

Chapman, Davis, and Greenberg reported on their new models of asteroid fragmentation processes and collisional evolution. These ideas have evolved considerably since the 1960's when Kuiper, Anders, and others viewed the "bump" in the asteroid magnitude-frequency diagram as suggesting that only the relatively small asteroids are collisional fragments. Asteroid cross-sections are now known to be much larger than was previously thought, due to advances in measuring asteroid albedos. In 1975, Chapman and Davis reported collisional models showing that all but the very largest asteroids must be collisional fragments and suggesting that the asteroids might be a remnant from a vastly larger population of precursor bodies. Hypothesizing that the so-called S-type asteroids are mantle-stripped stony-iron cores of differentiated bodies, they even suggested an estimate of 300 times the present population for the early asteroid population.

The early asteroid models were consistent with the then-best evidence on the log-log size-frequency relation for the C (carbonaceous) and S (stony-iron) asteroids, with a straight-line (power-law) distribution for the C's, indicative of thorough collisional fragmentation of weak bodies and non-linear distributions for the supposedly incompletely fragmented, strong cores. But new bias-corrected asteroid statistics by Bowell and Zellner have shown the C asteroids to have a non-linear size distribution on the log-log plot.

Meanwhile, the Planetary Science Institute group improved several aspects of their collisional modelling. (1) Simultaneous collisional interaction of two distinct populations of bodies of very different strengths were modelled, simulating the C and S objects. (2) Laboratory data were employed to model the size of the largest and second-largest fragments in a catastrophic collision event as a function of the energy input to the target body by the projectile. They have discovered that many large weak (C-type) asteroids are fragmented by relatively energetic impacts that are nevertheless insufficient to disrupt the bodies against their own self-gravities. When more energetic impacts eventually disperse such already-fragmented bodies, the fragments are very small, resulting in a relative dearth of mid-sized C-type asteroids, consistent with the new size-frequency data.

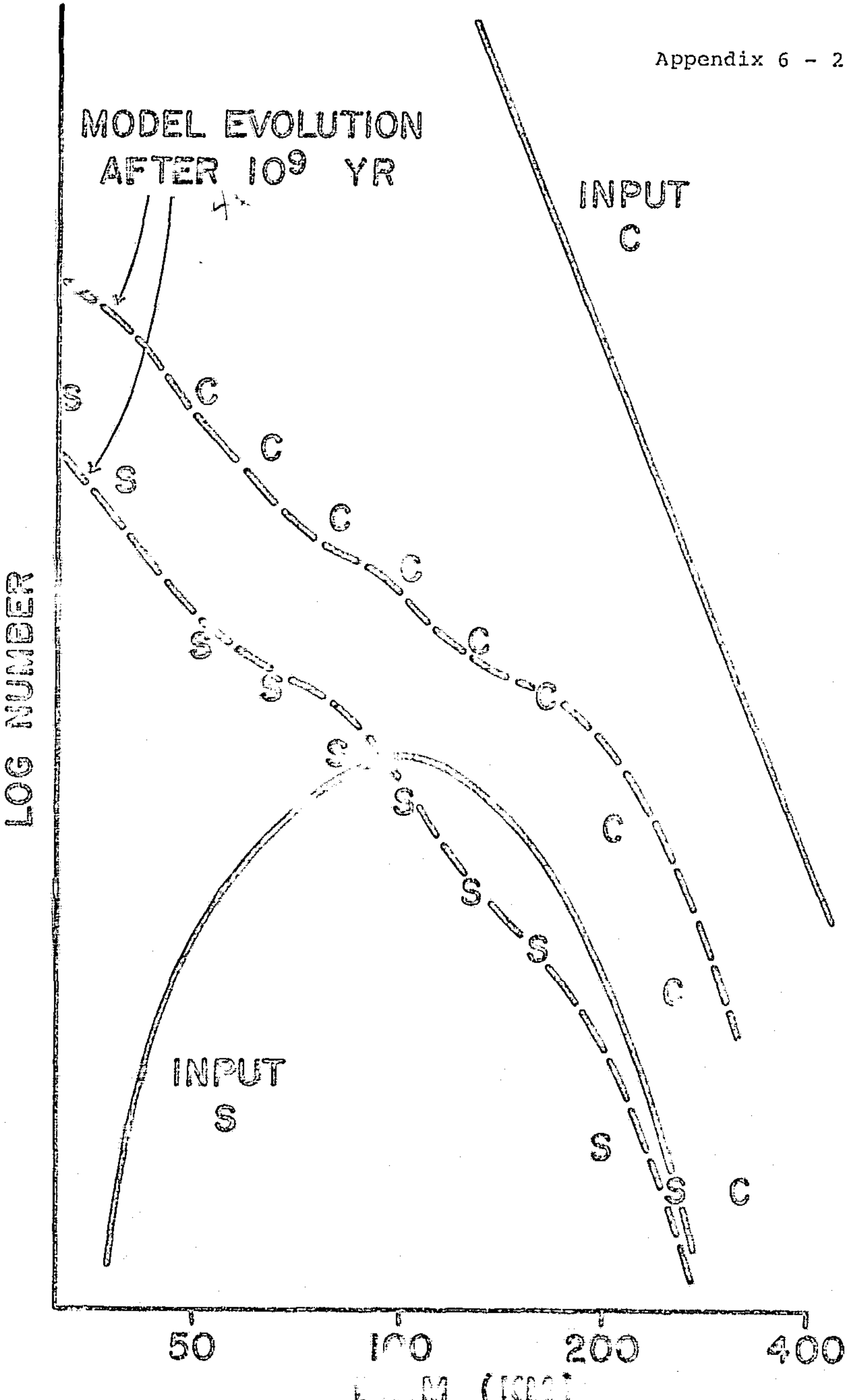
Some computer runs have successfully reproduced the essential features of the currently observed distributions, even for grossly augmented initial populations. But Chapman et al. are further revising the collisional model prior to investigating the effects of varying the input parameters to determine the range of initial conditions and physical parameters consistent with the currently observed asteroid belt.

APPENDIX 6

"Comparison of Chapman/Davis
Collisional Model with
Bias-Corrected Asteroid Data"

COMPARISON OF CHAPMAN/DAVIS COLLISIONAL MODEL WITH BIAS-CORRECTED ASTEROID DATA

The attached figure illustrates the degree to which the Chapman/Davis collisional evolution model for asteroids compares with observations. The asteroids were assumed to be composed of two different materials: strong metal (to simulate S-type asteroids) and very weak carbonaceous material (to simulate C-type asteroids). Input frequency distributions are shown with the solid lines. After 4×10^9 years of collisional evolution -- using nominal physical parameters in the model -- the distributions had evolved to the two broken lines. These may be compared with the real bias-corrected asteroid data compiled by Zellner and Bowell (in press in Proceedings of IAU Colloquium 39, 1977), indicated by the letters "S" and "C". Evidently, at least one set of initial conditions evolves to frequency relations very similar to those actually observed today.


MODEL EVOLUTION
AFTER 10^9 YR
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INPUT
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LOG NUMBER
50
100
200
400